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(54) **THERMAL MANAGEMENT SYSTEM FOR EMBEDDED ENVIRONMENT AND METHOD FOR MAKING SAME**

(75) Inventors: **Mehmet Arik**, Niskayuna, NY (US); **Charles Franklin Wolfe**, Albany, NY (US); **Yogen Vishwas Utturkar**, Latham, NY (US); **Charles Erklin Seeley**, Niskayuna, NY (US); **David Shannon Slaton**, Huntsville, AL (US); **William Henry Lueckenbach**, Charlottesville, VA (US)

Correspondence Address:
GENERAL ELECTRIC COMPANY
GLOBAL RESEARCH
PATENT DOCKET RM. BLDG. K1-4A59
NISKAYUNA, NY 12309

(73) Assignee: **GENERAL ELECTRIC COMPANY**, Schenectady, NY (US)

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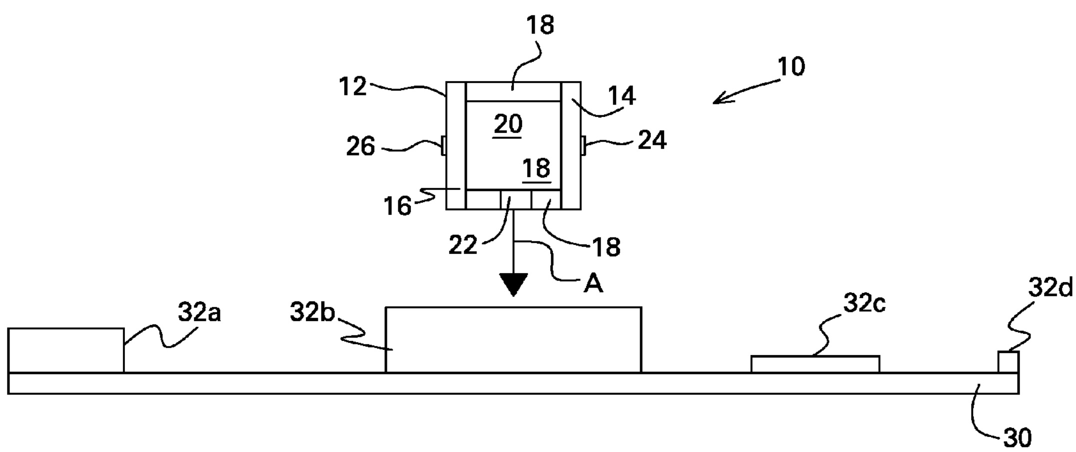
(57) **ABSTRACT**

A thermal management system for an embedded environment is described. The thermal management system includes a pleumo-jet that has at least one wall defining a chamber, at least one piezoelectric device on the at least one wall, and a compliant material within the at least one wall and encompassing the chamber. The compliant material has at least one opening providing fluid communication between said chamber and the embedded environment. A cooling system is also described. A method for making a pleumo-jet is also described.



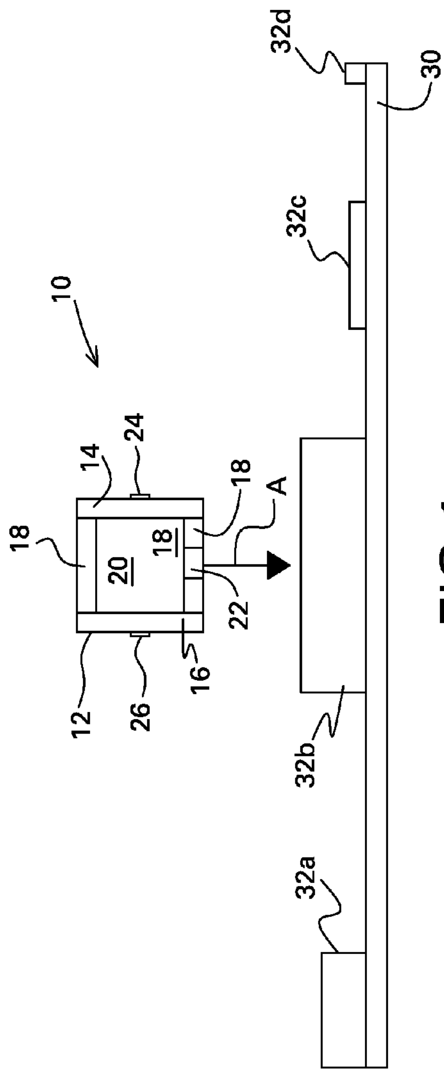

10
12
14
16
18
18
18
20
22
24
26
A
30
32a
32b
32c
32d

FIG.1

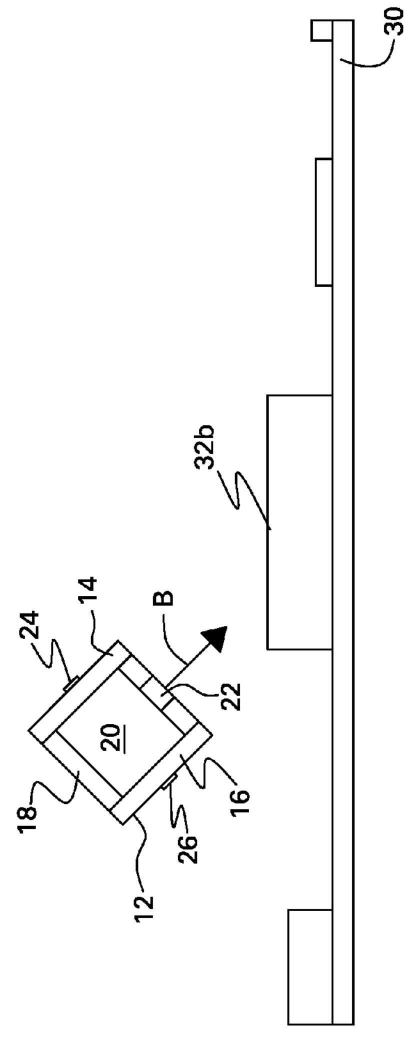

12
14
16
18
20
22
24
26
B
30
32b

FIG.2

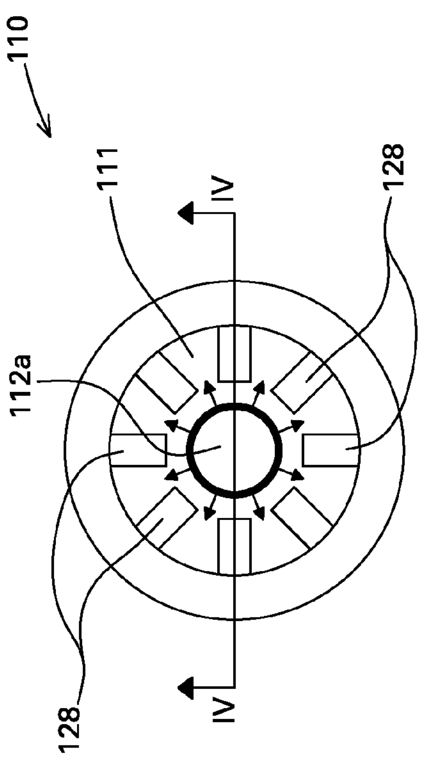

110
111
112a
128
128
IV
IV

FIG.3

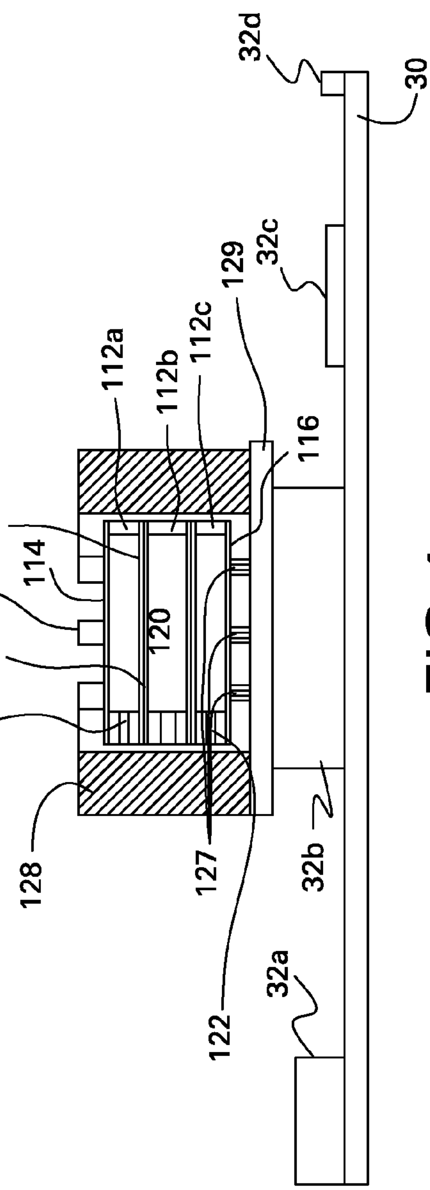

32d
30
32c
129
112a
112b
112c
116
116
114
114
120
122
122
128
127
32b
32a

FIG.4

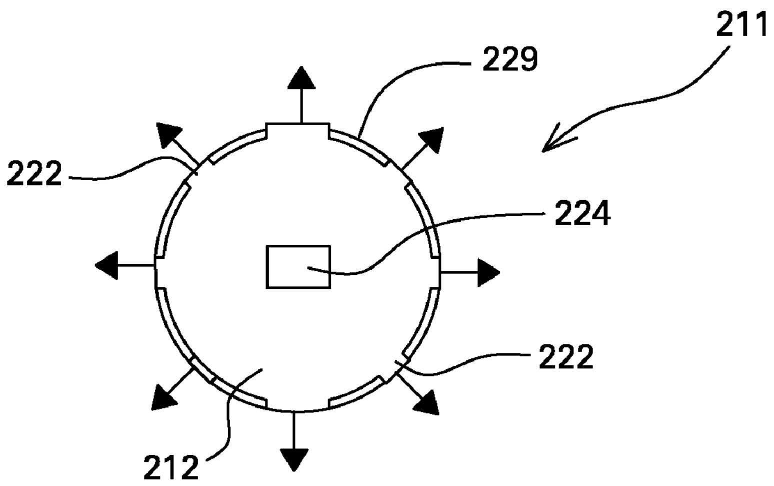


FIG.5

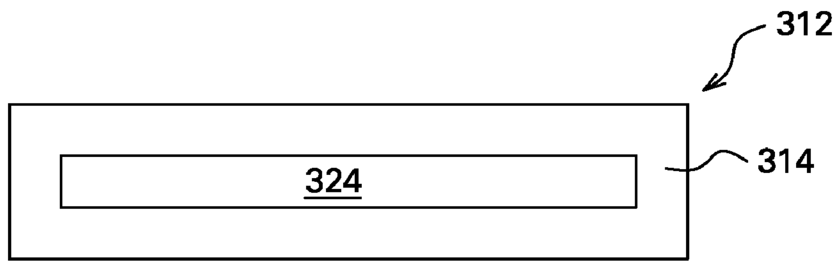


FIG.6

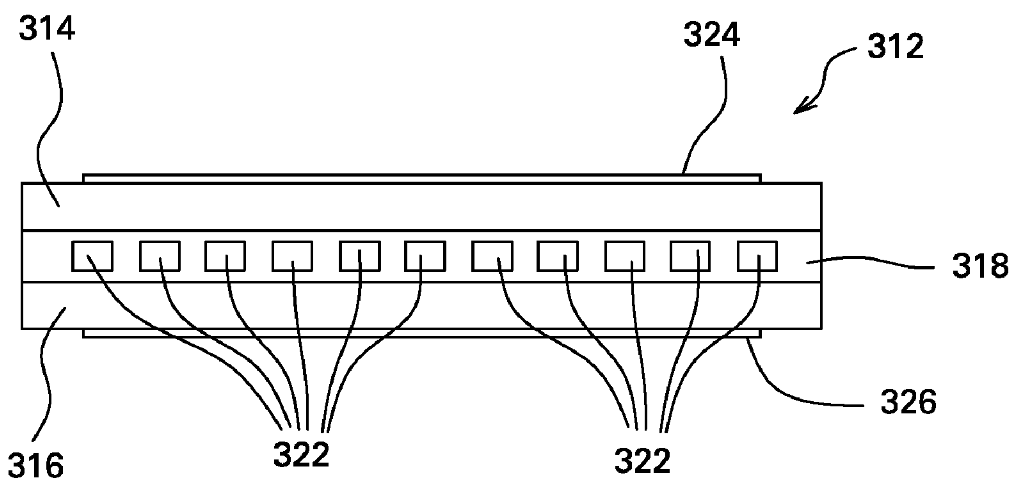


FIG.7

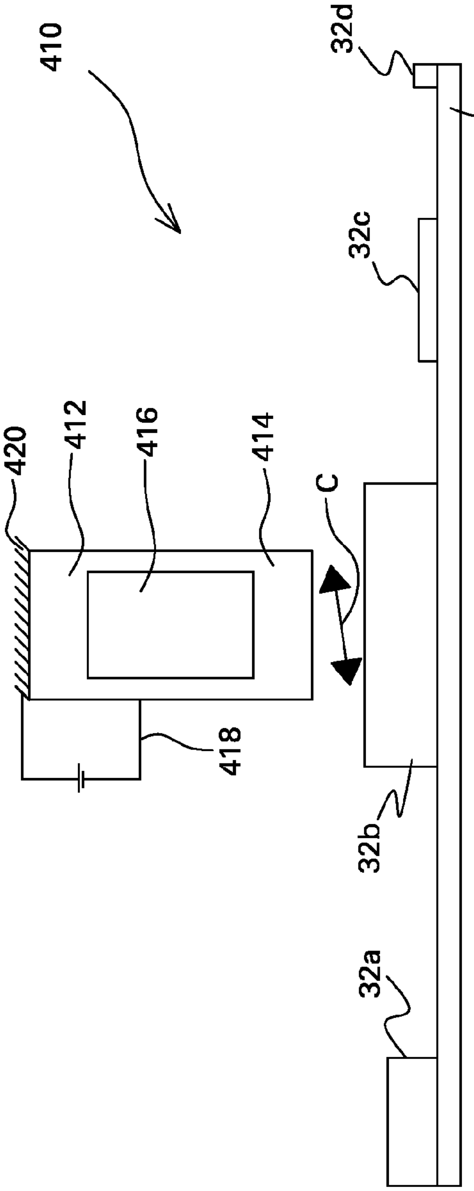

410
32d
30
32c
420
412
416
414
C
418
32b
32a

FIG. 8

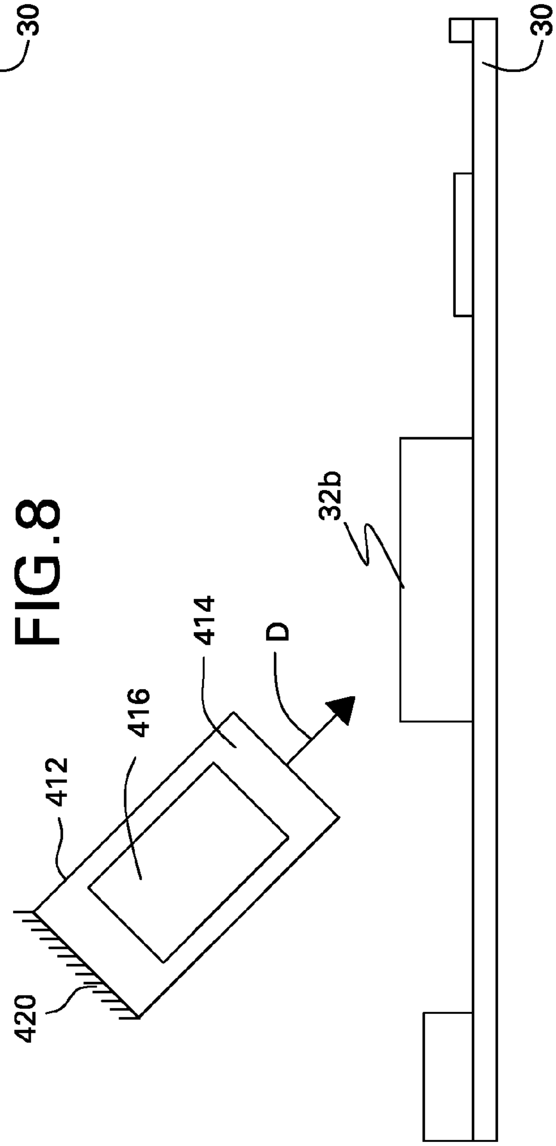
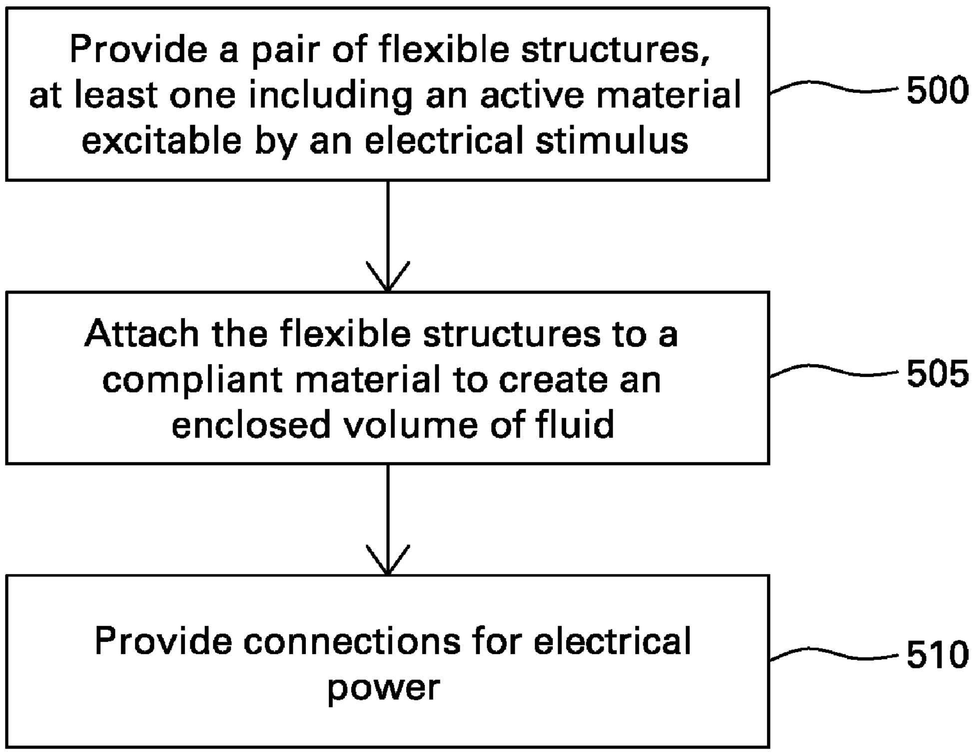

30
32b
414
D
416
412
420

FIG. 9



Provide a pair of flexible structures, at least one including an active material excitable by an electrical stimulus
500
Attach the flexible structures to a compliant material to create an enclosed volume of fluid
505
Provide connections for electrical power
510

FIG.10

THERMAL MANAGEMENT SYSTEM FOR EMBEDDED ENVIRONMENT AND METHOD FOR MAKING SAME

BACKGROUND

[0001] The invention relates generally to thermal management systems, and more particularly to thermal management systems for use in embedded environments.

[0002] Environments having embedded electronic systems, hereinafter embedded environments or heated environments, offer challenges for thermal management. Such systems produce waste heat as a part of their normal operation, heat that must be removed for proper performance and reliability of the embedded electronics. The design of thermal management systems to provide cooling for embedded electronics is a formidable challenge due to space limitations. Examples of embedded electronic systems include single board computers, programmable logic controllers (PLCs), operator interface computers, laptop computers, cell phones, personal digital assistants (PDAs), personal pocket computers, and other small electronic devices, there is a limited amount of available space for thermal management systems. It has been known to use passive cooled heat sinks or forced air-cooling as thermal management systems to assist in the removal of heat from electronic components. Further, it has been known that conducting the heat generated by electronic components to a printed circuit board, on which they are mounted, thereby providing a migration of the heat from a smaller area to a larger area.

SUMMARY

[0003] The invention includes embodiments that relate to a thermal management system for a heated environment that includes a pleumo-jet. The pleumo-jet includes at least one wall defining a chamber, at least one active material on the at least one wall, and a compliant material within the at least one wall and encompassing the chamber. The compliant material has at least one opening facilitating fluid communication between the chamber and the heated environment.

[0004] The invention includes embodiments that relate to a pleumo-jet that includes a first flexible structure, a second flexible structure, at least one active material on at least one of the first and second flexible structures, and a compliant material positioned between the first and second flexible structures and defining a chamber. The compliant material includes at least one orifice for facilitating fluid communication between the chamber and an ambient environment.

[0005] The invention includes embodiments that relate to a cooling system for a heated environment. The cooling system includes a substrate having one free end and one anchored end, at least one piezoelectric device positioned on the substrate, and an electrical circuit to provide an electrical current to the at least one piezoelectric device.

[0006] The invention includes embodiments that relate to a method for making a pleumo-jet. The method includes providing a pair of flexible structures, at least one of the structures having an attached active material, attaching a compliant material between the pair of flexible structures, the elastomeric material having at least one orifice, and adding electrical contacts to the pair of flexible structures.

[0007] These and other advantages and features will be more readily understood from the following detailed description of preferred embodiments of the invention that is provided in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. **1** is a cross-sectional side view of a thermal management system utilizing a pleumo-jet constructed in accordance with an embodiment of the invention.

[0009] FIG. **2** is a cross-sectional side view showing the thermal management system of FIG. **1** with the pleumo-jet in a different position.

[0010] FIG. **3** is a top view of a thermal management system constructed in accordance with an embodiment of the invention.

[0011] FIG. **4** is a cross-sectional side view of the thermal management system of FIG. **3** taken along line IV-IV.

[0012] FIG. **5** is a top view of a pleumo-jet constructed in accordance with an embodiment of the invention.

[0013] FIG. **6** is a top view of a pleumo-jet constructed in accordance with an embodiment of the invention.

[0014] FIG.**7** is a side view of the pleumo-jet of FIG. **6**.

[0015] FIG. **8** is a schematic view a thermal management system utilizing a piezoelectrically driven flexible cooling apparatus constructed in accordance with an embodiment of the invention.

[0016] FIG. **9** is a schematic view showing the thermal management system of FIG. **8** with the piezoelectrically driven flexible cooling apparatus in a different position.

[0017] FIG. **10** illustrates process steps for forming a pleumo-jet in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

[0018] Referring to FIGS. **1** and **2**, there is shown a thermal management system **10** that includes a pleumo-jet **12** illustrated in cross-section and placed in proximity to a printed circuit board assembly (PCA) **30** having a plurality of electronic components to be cooled $\mathbf{32}_{a-d}$. While a PCA **30** is depicted with reference to an embodiment of the invention, it should be appreciated that the thermal management system **10** may be utilized in any suitable embedded environment and its depiction with reference to the PCA **30** is merely for convenience in description. The PCA **30** may be used in heated environments in any number of small electronic devices, such as, for example, single board computers, programmable logic controllers (PLCs), laptop computers, cell phones, personal digital assistants (PDAs), personal pocket computers, to name a few. The pleumo-jet **12** is sized appropriately for its use, and generally is in the meso-scale or micro-scale.

[0019] The pleumo-jet **12** is positioned such that a pulsating fluid stream of ambient air can be generated from the apparatus **12** and directed at the electronic components to be cooled $\mathbf{32}_{a-d}$. As shown, in FIG. **1**, a fluid stream of ambient air, or other fluid, is directed along direction A toward the electronic component to be cooled $\mathbf{32}_b$. Alternatively, the pleumo-jet **12** may be positioned to direct a fluid stream of ambient air along direction B toward the electronic component to be cooled $\mathbf{32}_b$ (FIG. **2**).

[0020] The pleumo-jet **12** includes a first structure or wall **14** and a second structure or wall **16**. The walls **14**, **16** are formed of a flexible material, such as, for example, metal, foil, plastic, or polymer composite material. A compliant material **18** is positioned between the pair of walls **14**, **16**, and the combination of the walls **14**, **16** and the compliant material **18** define a chamber **20**. At least one orifice **22** provides a channel between the chamber **20** and the environment outside the apparatus **12**. Although a pair of opposing walls **14**, **16** are depicted, it should be appreciated that instead of two walls, a single wall (wrapping around to form a cylinder) along with the compliant material **18** may form a pleumo-jet, such as the pleumo-jet **12**.

[0021] Positioned on at least one of the walls **14**, **16** is an active material, such as, for example, a piezoelectric material. As shown, active materials **24** and **26** are positioned, respectively, on walls **14** and **16**. A suitable active material is one which is capable of creating stress resulting from an electrical stimulus. Examples of suitable active material include piezoelectric material, magnetostrictive material (magnetic fields from coils attract/oppose one another), shape-memory alloy, and motor imbalance (motor with a mass imbalance creates oscillatory motion). Within the subset of piezoelectric materials, suitable active materials include bimorph piezoelectric configurations, where two piezo layers are energized out of phase to produce bending; thunder configurations, where one piezo layer is disposed on a pre-stressed stainless steel shim; buzzer element configurations, where one piezo layer is disposed on a brass shim; and MFC configurations, where a piezo fiber composite on a flexible circuit is bonded to a shim.

[0022] The active material **24**, **26** may incorporate a ceramic material. Electrical circuitry (schematically depicted in FIG. **8**) is attached to the pleumo-jet **12** to provide an electrical current to one or both of the active material **24**, **26**. The current may be provided as a sine wave, a square wave, a triangular wave, or any other suitable waveform, and it should be appreciated that the current is not to be limited to any specific wave form. Specifically, it has been found that currents having lower harmonics, such as, for example, a sine wave may be used to provide a quieter pleumo-jet **12**.

[0023] FIGS. **3** and **4** illustrate a thermal management system **110** in accordance with another embodiment of the invention. The thermal management system **110** includes a pleumo-jet system **111**, which has a plurality of pleumo-jets in a stacked arrangement. As shown, the pleumo-jet system **111** includes pleumo-jets **112**$_a$, **112**$_b$, and **112**$_c$ in a stacked arrangement. The pleumo-jet **112**$_c$ is positioned over a base **129** and supported in that location with one or more supports **127**. The pleumo-jets **112**$_a$, **112**$_b$, and **112**$_c$ have a similar construction to the pleumo-jet **12** (FIGS. **1**, **2**), with the optional exception of the orifices. Specifically, each of the pleumo-jets **112**$_a$, **112**$_b$, and **112**$_c$ includes flexible walls and a compliant material defining a chamber **120**, and each of the flexible walls has one or more active materials (not shown). Supports between the pleumo-jets **112**$_a$, **112**$_b$, and **112**$_c$ are necessary to provide sufficient room to accommodate the active materials on one or both flexible walls of each pleumo-jet.

[0024] Each pleumo-jet **112**$_a$, **112**$_b$, and **112**$_c$ may include a single orifice **122** extending from the chambers **120** through the compliant material. The pleumo-jet system **111** may be arranged such that each of the single orifices **122** of each pleumo-jet **112**$_a$, **112**$_b$, and **112**$_c$ is positioned in the same direction (FIG. **4**). Alternatively, each of the single orifices **122** may be positioned to direct ambient air in a different direction than the other single orifices **122** (FIG. **3**). For any two adjacent orifices **122**, the separation between the orifices **122** may be in a range between just above zero degrees (0°) to less than ninety degrees (90°). In one embodiment, adjacent orifices **122** may be separated by a range of about 5° to about 45°.

[0025] The pleumo-jets **112**$_a$, **112**$_b$, and **112**$_c$ are surrounded by fins **128**, which are supported on the base **129**. The fins **128** assist in increasing the surface area for heat transfer for cooling the electronic components **32**$_{a-d}$. As with the previously described pleumo-jet **12**, the pleumo-jets **112**$_a$, **112**$_b$, and **112**$_c$ utilize active material, for example a piezoelectric material (not shown), to form streams of ambient air. Briefly, electrical current from electrical circuitry (shown in FIG. **8**) is received by the active material, and transformed into mechanical energy. The electrical current can take the form of a sine wave, a square wave, a triangular wave, or any other suitable wave form. The voltage level for the electrical current may be between 1 and 150 volts but is not so limited. The frequency of the current may be between 2 and 300 hertz for embodiments requiring reduced noise, and between 300 hertz and 15 kilohertz for embodiments that do not require reduced noise levels.

[0026] The active material creates stress on the flexible walls, causing them to flex inwardly, resulting in a chamber volume change and an influx of ambient air into the chambers **120**, and then outwardly, thereby ejecting the ambient air from the chambers **120** via the orifices **122**.

[0027] Another alternative embodiment of a pleumo-jet system is illustrated in FIG. **5**. Specifically, a pleumo-jet system **211** is illustrated as including a base **229** supporting a pleumo-jet **212**. The pleumo-jet **212** has a plurality of orifices **222**, each extending outwardly in different radial directions. An active material **224** is shown on a surface of a flexible wall of the pleumo-jet **212**. For any two adjacent orifices **222**, the separation between the orifices **222** may be in a range between just above 0° to less than 90°. In one embodiment, adjacent orifices **222** may be separated by a range of about 5° to about 45°.

[0028] FIGS. **6** and **7** illustrate a pleumo-jet **312**. The pleumo-jet **312** includes a first flexible wall or structure **314**, a second flexible wall or structure **316**, and a compliant material **318** positioned between the flexible walls **314**, **316**. The walls **314** and **316** are rectangular in shape and, together with the compliant material **318**, form a chamber (not shown). Orifices **322** extend out through the compliant material **318** from the chamber to the ambient environment. An active material **324** is positioned on the wall **314**, and optionally an active material **326** may be positioned on the wall **316**. The active material can be activated with an electric current provided by electrical circuitry (not shown) to create stress on the wall(s) **314** (and **316**) to allow for the ingestion of ambient air into the chamber and the expulsion of the ambient air from the chamber to the ambient, heated environment.

[0029] FIGS. **8** and **9** illustrate another embodiment of a thermal management system. A thermal management system **410** is illustrated as including a piezoelectric fan apparatus **412** in working relationship with a PCA **30** containing electronic components to be cooled **32**$_{a-d}$. The piezo fan apparatus **412** includes one free end and one end fixed to a support member **420**. The piezo fan apparatus includes a substrate **414** and an active material **416**. The active material **416** may utilize, for example, a piezoceramic material.

[0030] An electrical circuit **418** is connected to the piezo fan apparatus **412**. Running an electrical current through the piezo fan apparatus **412** sends an electrical charge through the active material **416**. The active material **416** transforms the electrical energy into mechanical energy by creating a stress on the substrate **414**, causing it to rotate about the fixed end. This creates a current of ambient air to travel in a direction C (FIG. **8**) or in a direction D (FIG. **9**), depending upon the positioning of the piezo fan apparatus **412** relative to the electronic components to be cooled $\mathbf{32}_{a-d}$.

[0031] Next, and with specific reference to FIG. **10**, will be discussed a process for forming a pleumo-jet in accordance with an embodiment of the invention. At Step **500**, a pair of flexible structures is provided. The flexible structures may be metallic or they may be non-metallic, such as plastic or polymer composite material. Examples of the flexible structures include flexible walls **14**, **16** (FIGS. **1**, **2**) and flexible walls **314**, **316** (FIGS. **6**, **7**). One or both of the flexible structures require an active material that is excitable by an electrical stimulus to be affixed thereon. Suitable examples of active material include material **24**, **26** (FIGS. **1**, **2**) and material **324**, **326** (FIGS. **6**, **7**).

[0032] At Step **505**, a compliant material is attached between the flexible structures. The compliant material may be compliant material **18** (FIGS. **1**, **2**) or compliant material **318** (FIGS. **6**, **7**). The compliant material is to be provided in such a form as to define a chamber between the flexible structures. One process for providing the compliant material is to dispense the compliant material in a liquid or semi-liquid form onto one of the flexible structures, placing the other conductive structure on the compliant material, and allowing the compliant material to dry. A liquid silicone-based material may be suitable for such a process. Another process for providing the compliant material is to cut the compliant material from a pre-made sheet of compliant material, and bonding the pre-made sheet of cut compliant material to the flexible structures. A pre-made silicone-based sheet of material may be suitable for this process.

[0033] At Step **510**, electrical contacts are provided to the flexible structures. Electrical circuitry will be attached to the electrical contacts.

[0034] While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed as new and desired to be protected by Letters Patent of the United States is:

1. A thermal management system for a heated environment, comprising:

a pleumo-jet, comprising:

at least one wall defining a chamber;

at least one active material on said at least one wall; and

a compliant material within said at least one wall and encompassing said chamber, said compliant material having at least one opening facilitating fluid communication between said chamber and the heated environment.

2. The thermal management system of claim **1**, wherein said compliant material comprises an elastomeric material.

3. The thermal management system of claim **1**, comprising an electrical circuit to provide an electrical current to said pleumo-jet.

4. The thermal management system of claim **3**, wherein said electrical current is one exhibiting lowered harmonics.

5. The thermal management system of claim **4**, wherein said electrical current omprises a sine wave.

6. The thermal management system of claim **1**, wherein the heated environment includes single board computers, programmable logic controllers (PLCs), operator interface computers, laptop computers, cell phones, personal digital assistants (PDAs), and personal pocket computers.

7. The thermal management system of claim **1**, wherein the heated environment comprises at least one heated body.

8. The thermal management system of claim **7**, wherein said at least one opening is positioned to eject an ambient fluid directly on said at least one heated body.

9. The thermal management system of claim **8**, wherein said at least one opening is at an angle transverse to an upper surface of the at least one heated body.

10. The thermal management system of claim **1**, wherein said elastomeric material comprises a plurality of openings facilitating fluid communication between said chamber and the heated environment.

11. The thermal management system of claim **10**, wherein said at least one wall has a circular profile.

12. The thermal management system of claim **10**, wherein said at least one wall has a rectangular profile.

13. The thermal management system of claim **1**, comprising:

a base upon which said pleumo-jet is positioned; and

a plurality of fins surrounding said pleumo-jet.

14. The thermal management system of claim **13**, comprising a plurality of pleumo-jets positioned on said base in a stacked arrangement.

15. The thermal management system of claim **1**, wherein said pleumo-jet comprises a pair of walls sandwiching said elastomeric material, each of said walls having said at least one piezoelectric device.

16. A pleumo-jet, comprising:

a first flexible structure;

a second flexible structure;

at least one active material on at least one of said first and second flexible structures; and

a compliant material positioned between said first and second flexible structures and defining a chamber, wherein said compliant material comprises at least one orifice for facilitating fluid communication between said chamber and an ambient environment.

17. The pleumo-jet of claim **16**, comprising an electrical circuit to provide an electrical current to the at least one active material.

18. The pleumo-jet of claim **16**, wherein said compliant material comprises an elastomeric material.

19. The pleumo-jet of claim **16**, wherein said apparatus is no larger than meso-scale sized.

20. The pleumo-jet of claim **16**, wherein said at least one active material comprises a piezoceramic material.

21. The pleumo-jet of claim **16**, wherein said at least one active material is positioned on both of said first and second flexible structures.

22. A cooling system for a heated environment, comprising:

a substrate having one free end and one anchored end;

at least one piezoelectric device positioned on said substrate; and

an electrical circuit to provide an electrical current to the at least one piezoelectric device.

23. The cooling system of claim **22**, wherein the heated environment includes single board computers, programmable logic controllers (PLCs), operator interface computers, laptop computers, cell phones, personal digital assistants (PDAs), and personal pocket computers.

24. The cooling system of claim **22**, wherein said substrate is no larger than meso-scale sized.

25. A method for making a pleumo-jet, comprising:

providing a pair of flexible flexible structures, at least one of the structures having an attached active material;

attaching a compliant material between the pair of flexible structures, said elastomeric material having at least one orifice; and

adding electrical contacts to the pair of flexible structures.

26. The method of claim **25**, wherein said providing comprises providing attached active material for each of the pair of flexible flexible structures.

27. The method of claim **25**, wherein said attaching comprises attaching an elastomeric material between the pair of flexible structures.

28. The method of claim **25**, wherein said attaching comprises:

dispensing the compliant material as a semi-liquid silicone-based material;

contacting the semi-liquid silicon-based material with one of the flexible structures; and

placing the other of the flexible structures in contact with the semi-liquid silicone-based material.

29. The method of claim **25**, wherein said attaching comprises:

forming the compliant material from a pre-made sheet of silicone-based material; and

bonding the compliant material to the pair of flexible structures.

* * * * *